THE IMPORTANCE OF WATER COLOUR IN DETERMINING CONTEMPORARY DIATOM ASSEMBLAGES AND THE IMPLICATIONS ON DOWN-CORE pH RECONSTRUCTION

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Abstract

Diatom assemblages in surficial sediments of selected Nova Scotian and Newfoundland lakes are discussed with respect to water quality and drainage basin characteristics. Calculated Nygaard log alpha values in the highly coloured, low pH lakes were negative, indicating that these lakes are dominated by algal species which have been classified in the literature as being alkaliphilous. Relationships between pH and log alpha values have similar slopes but much lower intercepts than equations presented in the literature, suggesting that coloured lakes behave differently from clearwater lakes. Water colour is shown to be an important determinant of diatom composition and thus must be considered when attempting to reconstruct down-core pH histories using transfer functions derived from relationships between pH and surficial sediment diatom composition.

RESUME

Des assemblages de diatomées, observés dans des échantillons de sédiments superficiels provenant de certains lacs de la Nouvelle-Écosse et de Terre-Neuve, sont discutés en tenant compte de la qualité de l'eau de ces lacs et des caractéristiques de leur bassin-versant. Des valeurs calculées de log alpha (selon Nygaard), pour des lacs très colorés dont le pH est bas, furent négatives. Ceci indique que ces lacs sont dominés par des espèces d'algues qui ont été classées, selon la littérature scientifique, comme étant des espèces alcalinophiles. Les équations des relations entre le pH de ces lacs et les valeurs de log alpha présentent des pentes semblables mais des ordonnées à l'origine beaucoup plus faibles que celles des équations retrouvées dans la littérature scientifique. Ceci suggère que les lacs colorés se comportent différemment des lacs dont les eaux sont claires. Il est démontré que la couleur de l'eau est un facteur déterminant de la composition des diatomées. Donc, la couleur de l'eau doit être considérée lorsque l'on tente de reconstruire l'historique du pH d'un lac en relation avec la profondeur des sédiments de fond, en utilisant des fonctions de transfert déterminées à partir des relations entre le pH et la composition des diatomées dans les sédiments superficiels des lacs.

Introduction

Attempts to document recent acidification of surface waters have been hindered by the lack of reliable long term records of pH. To overcome this shortage of data, numerous authors (Krauss-Dellin & Steinberg 1984; Davis et al. 1985) have used paleolimnological records of selected taxa as a means of reconstructing lake pH histories. Hustedt (1939) classified diatoms according to their ecological requirements and established a series of five pH preference groups. Based on these pH groups, Nygaard (1956) developed three indices which were used to relate diatom remains in Lake Gribso to historical pH records. The validity of these indices has been reviewed by Merilainen (1967) and the logarithm of the Nygaard alpha index versus pH relationship is used widely as a tool for reconstructing downcore pH histories (Dickman et al. 1984; Delorme et al. 1982). In addition to the Nygaard index, transfer functions have been derived using other indices (Renberg and Hellberg 1982), indicator diatom species (Davis & Anderson 1985) and results from principle component analysis (Davis et al. 1985). Despite the popularity of paleolimnological techniques, several authors (Battarbee & Flower 1984; Davis & Anderson 1985) have noted that downcore pH prediction using these transfer functions may be subject to considerable inaccuracy.

The Water Quality Branch, Atlantic Region, presently

monitors 78 lakes in Nova Scotia and Newfoundland as part of the LRTAP (Long Range Transport of Atmospheric Pollutants) Monitoring program. These lakes were chosen from the NAQUADAT data base using cluster analysis based on seven LRTAP related water quality parameters. During May, 1984, surficial sediment samples were collected from 45 of these lakes for diatom identification and enumeration. These samples were collected to provide a background characterization of the diatom populations of the monitored lakes and to assess whether diatom composition could be used as a tool for confirming changes in water quality conditions of the LRTAP monitoring lakes. This paper not only examines the relationship between pH and diatom composition but also considers the importance of water colour as a determinant of lake diatom flora.

Methods

All sampling for both water and sediment samples was conducted from a helicopter equipped with floats. Surficial sediment samples were collected from the deepest point of each lake using a 244 cm^2 Ponar dredge. The top 2.5 cm of sediment was sectioned and transferred to plastic bags. Each sample was fixed with 5 mL of 4% formalin in the field and frozen until analysis. All water chemistry measurements were made at the Water Quality Branch laboratory using methods outlined in the Analytical Methods Manual (Environment Canada, 1979). Water quality data presented in Table 1 are the median values for

three years of lake monitoring.

Quantitative analysis of the phytoplankton was carried out by using an inverted microscope, a Sedgewick-Rafter counting chamber or a Hemocytometer combined with sediment and dilution techniques according to procedures given in Standard Methods (1971). Diatom analysis was performed after centrifuging or sedimenting and acid cleaning the sample.

Diatoms were classed according to the pH categories (Hustedt (1939) using preferences given by Nygaard (1956), Merilainen (1967) and Beaver (1981). Nygaard log α values were calculated using the following equation.

$$\log \alpha = \log\left(\frac{5 \times ACB + AC}{5 \times ALB + AL}\right)$$

where ACB = % acidobiontic
AC = % acidophilous
ALB = % alkalibiontic
AL = % alkaliphilous

For sites which had no acid units, the alpha value was estimated as the inverse of the alkaline units. All data manipulation and statistical analysis were performed on a VAX 11/750 using the RS1 data management system.

Results

Tables 1 and 2 present the Nygaard log α values and relevant water quality conditions for 28 Nova Scotian and 17

Newfoundland lakes. The locations of these sites are given in Figure 1.

These data have been subdivided into two sets as a means of identifying possible geographic differences in the response of diatom taxa to acidification. The log α values presented in Tables 1 and 2 are generally negative, indicating that these lakes are dominated by species which are considered to be alkaliphilous. This is true even for those lakes located in Kejimkujik National Park (lakes 1 to 15 of Table 1) which exhibit chronically depressed pH levels. Figures 2 and 3 present the relationships between log α and pH for the Nova Scotian and Newfoundland lakes respectively. The linear relationships are poor for both data sets, having coefficients of determination of 0.31 and 0.34 respectively. From Figure 2, it is readily apparent that, with a few exceptions, the Yarmouth and Kejimkujik lakes have dissimilar log α and pH relationships. Considering the Kejimkujik lakes alone, the relationship between log α and pH improves considerably as indicated by an increase in the coefficient of determination from 0.31 to 0.67. The Newfoundland lakes exhibit a range of log α values similar to those observed for the Kejimkujik lakes even though the pH values are generally much higher. The lakes situated on the south and west coast of Newfoundland have a good linear relationship between log α and pH with a coefficient of determination of 0.87. The lakes located in Terra Nova National Park tend to cluster around this regression line, however they

exhibit no obvious log α and pH relationship. The site from Gros Morne National Park is a coloured, high altitude pond which behaves in a fashion similar to the Kejimkujik lakes.

Table 3 presents the multiple linear regression analysis between pH, log α and water colour for the Nova Scotian and the Newfoundland lakes. Other water quality parameters and morphometric features were considered in the regression analysis, but were either insignificant or had little effect on the overall coefficient of determination. Water colour cannot explain the difference between the Kejimkujik and Yarmouth lakes and thus does not improve the relationship for the entire Nova Scotian lake data set. However, water colour is an important parameter for the Kejimkujik lakes and when it is included, the regression analysis increases the coefficient of determination from 0.67 to 0.85. Water colour differences also appear to explain some of the scatter observed for the Newfoundland log α vs pH relationship. Excluding the Gros Morne lake, multiple linear regression analysis between pH, log α and water colour has a coefficient of determination of 0.61. Linear regression of log α against pH for this data set results in a coefficient of determination of 0.49.

Table 4 presents the multiple linear regression analysis for percent composition of selected diatom taxa against pH for the Kejimkujik lakes and the entire Newfoundland data set. With the exception of Melosira distans which was abundant in both

data sets, the diatoms were grouped by genera for development of the transfer function. Of the ten taxa considered, seven were found to be significant for the Kejimkujik lakes and the overall equation had a coefficient of determination of 0.93. Of these seven taxa all but Fragilaria sp. were negatively correlated with pH. Using the entire Newfoundland data set, six of the ten taxa considered were found to be significant and the coefficient of determination for the regression equation was 0.86. Of the six taxa included in the equation only Pinnularia sp. was positively related to pH. Of the ten taxa considered, four were common to both regression equations. Of these four, only one genera (Pinnularia) exhibited slopes with opposite signs in the two transfer functions.

Discussion

Dickman et al. (1984) have indicated that geographic differences in the response of diatom taxa to acidification cannot be overlooked and that it is necessary to employ regionally derived log α and pH relationships for inferring downcore pH histories. They also presented a summary of log and pH relationships from six studies in North America and Scandinavia (see Table 5) which indicated that the slopes and to a lesser extent the intercepts of the linear regression equations can be highly variable.

The data from the Nova Scotian lakes indicate that appreciable differences in the response of diatoms to pH can occur within small geographical areas. Huttunen and Merilainen (1983) observed that diatom assemblages in 49 Finnish lakes were dependent on lake physico-chemistry as well as anthropogenic activities within the drainage basin. The lakes in Kejimkujik National Park are subject to minimal human disturbance and are characteristically dilute, with low pH values and high water colours. Cluster analysis of the Nova Scotia lakes ordinates the Kejimkujik lakes into two water quality cluster groups, indicating that these lakes are essentially similar. As lake diatom composition is largely dependent on lake chemistry and the drainage basin biophysical conditions, a good relationship between log α and pH is to be expected for the Kejimkujik lakes. The Yarmouth lakes are situated near the coast and are subject

to varying levels of anthropogenic activity. The marine influence is reflected by higher specific conductance and pH levels, even in three coloured lakes which would be expected to be naturally acidic. The two Yarmouth lakes which have log and pH values similar to those observed for the Kejimkujik lakes, are both dilute highly coloured lakes with low pH. The Yarmouth lakes ordinate into five water quality cluster groups which indicates their diverse chemical characteristics. Thus the heterogeneity of water quality and biophysical conditions of these lakes may explain the variable response of algal taxa to pH, both between the Yarmouth and Kejimkujik lakes and within the Yarmouth data set. Heterogeneity of water quality and biophysical conditions may also explain some of the scatter observed for the Newfoundland log α and pH relationship, particularly for the high elevation lake in Gros Morne National Park.

The regression equation for the Kejimkujik log α, pH relationship has a slope of -.77 which is within the range of slopes observed by other investigators (Dickman et al. 1984) (Table 5). However the intercept of 4.49 is considerably lower than those presented in the literature. Similarly, the Newfoundland mainland lakes have a similar slope and a lower intercept than the six equations presented by Dickman et al (1984). Several authors (Vaughan et al. 1981 1983; Delorme et al. 1982) have noted that highly coloured waters with low pH values, have diatom floras comprised of a higher percentage of

literature defined alkaliphilous species than would be expected. This is true for the naturally acidic, highly coloured lakes in Kejimkujik and to a lesser extent for the moderately coloured Newfoundland sites and is reflected by the reduced intercepts for the two regression equations. Thus it appears that water colour which is an indicator of the chemical conditions of organic waters, may be an important determinant of diatom species composition. The role of water colour in determining algal composition has been illustrated by Huttunen and Merilainen (1983) who, using detrended correspondence analysis (Decorana), observed that the humic lakes formed distinct diatom assemblage clusters. In addition, Davis et al. (1984) observed that indicator diatom taxa in 35 Norwegian lakes were well correlated with TOC (Total Organic Carbon) concentrations. The importance of water colour for the Kejimkujik and the Newfoundland lakes is supported by the increase in the coefficients of determination when water colour is included into the regression analysis between pH and log α.

Delorme et al. (1982) collected a sediment core from the moderately coloured Kejimkujik lake for stratigraphic analysis. However, lacking an appropriate calibration equation, these authors were forced to reconstruct the down-core pH history of Kejimkujik lake using equations derived for clear water lakes given by Norton et al. (1981) and Del Prete et al. (1981). Using these equations, the surficial sediment diatom assemblage predicted a pH of 6.9 which is 1.9 pH units greater than the

present Kejimkujik Lake pH (1981-1985 Median value = 5.0). Substituting the surficial log α value of -.42 into the Kejimkujik lakes calibration equation, results in a predicted pH of 4.8 which is only 0.2 pH units lower than the observed pH. Similarly, using the multiple linear regression equation presented in Table 3, the Kejimkujik lake pH is predicted to be 4.9. This inability to calibrate the Kejimkujik lake core data using clear water derived equations and the close agreement between observed and predicted pH using the two Kejimkujik derived calibration curves further emphasizes the effect of water colour on lake diatom assemblages.

With the recognition that water colour can influence the lake diatom flora, the use of calibration curves for predicting down-core pH histories is not valid if water colour has varied over the period of the entire core. Although the assumption of constant water colour may be valid for short cores from lakes with a well documented history, it severely limits the ability to reconstruct the down-core pH history for lakes with short term historical records. Figure 4 presents the down-core pH reconstruction for Kejimkujik Lake using the Del Prete et al. (1981) calibration curve as well as the Kejimkujik derived relationship. The pH predicted by the Kejimkujik derived equation is reasonable for the first 6.6 cm of the core. However, prior to the increase in anthropogenic activity in the Kejimkujik basin circa 1850, this equation predicts that the pH was less than 4.0. Although pH values less than 4.0 have been

recorded for lakes in Atlantic Canada which have disturbed pyrite bearing slates (Kerekes et al. 1984), it is unlikely that a pristine lake in this area would exhibit this degree of natural acidity. Thus it appears that the coloured water calibration equation is not appropriate for the entire sediment core sequence. If it is assumed that the water colour of Kejimkujik lake increased with the onset of anthropogenic activities in the lake basin, then the reconstructed pH history below the 6.0 cm stratum would be shifted to the left. In the extreme case, if events circa 1840 resulted in a drastic shift from a clearwater to a coloured system then the Del Prete calibration curve may be valid for the 6.0 to 22. cm section of the sediment core and would indicate a reduction in Kejimkujik lake pH from 5.7 to 4.7. In actuality, without knowing the extent and timing of water colour variations of Kejimkujik lake it is impossible to establish a reliable pH reconstruction.

Although the use of diatom indices has been widely accepted, the difficulties of assigning diatom species to pH preference categories has prompted the development of transfer functions based on the abundance of selected algal taxa or the results of principle component analysis. Although the Kejimkujik and Newfoundland regression equations may be superior to the log α and pH relationships, they also are dependent on water colour conditions. Thus, the use of either log α , pH relationships or the diatom taxa transfer functions for stratigraphic pH reconstruction appears to be valid only if water colour has remained stable.

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Table 1: Selected Water Quality Parameters and Nygaard Log Alpha Values for the Nova Scotia LRTAP Monitoring Lakes

Lake	Distance from the Sea (Km)	Nygaard Log Alpha	pH	Alkalinity mg/l	Water Colour Hazen Units	Depth M	Specific Conductance uS/cm
1 Channel	36.00	-0.560	4.8	-0.8	100	2.0	27
2 Frozen Ocean	33.00	-0.570	4.9	-0.4	80	1.1	25
3 Little Red	39.00	-0.180	4.3	-2.0	120	0.5	35
4 Mount Tom	41.00	-0.240	4.5	-1.1	90	3.8	27
5 Big Dam	39.00	-0.560	5.0	-0.2	80	2.1	28
6 Mud	53.00	-0.005	4.9	-0.4	70	2.0	27
7 Back	48.00	-0.550	5.3	0.3	25	5.0	23
8 Mountain	46.00	-1.280	5.2	0.1	25	7.8	24
9 Beaverskin	45.00	-1.000	5.4	0.4	5	4.8	22
10 Snake	48.00	-0.370	4.8	-0.4	80	2.0	23
11 Pebbleloggitch	44.00	-0.460	4.5	-1.8	100	2.7	30
12 Ben	41.00	-0.135	4.7	-1.0	45	1.0	28
13 Luxion	39.00	-0.269	4.7	-1.2	80	3.0	36
14 George	49.00	-0.690	5.0	-0.4	70	4.0	29
15 McGinty	50.00	-1.550	5.9	1.7	45	3.8	24
16 Trefry	4.00	-1.900	5.9	2.0	40	18.0	64
17 Tedford	9.00	-0.140	6.1	2.0	5	2.5	42
18 Bird	11.00	-1.120	6.2	-0.4	5	5.0	44
19 Pierce	5.50	-0.320	5.6	0.7	25	2.9	45
20 Churchill	0.75	-1.960	6.3	4.1	20	5.9	96
21 Aliens	0.50	-0.480	6.3	3.8	20	5.5	87
22 Cedar	2.50	-0.630	6.1	1.5	30	5.0	62
23 Coggins	3.00	-1.830	6.0	1.8	80	2.0	53
24 Doctor	3.00	-1.790	6.1	0.6	120	6.0	62
25 Milo	1.00	-0.119	6.1	2.4	110	5.2	68
26 Brenton	5.00	-0.410	4.8	-0.2	160	2.8	46
27 Lower Cornings	4.00	-0.090	5.6	0.6	35	1.5	47
28 Snarl	10.00	0.045	4.9	-0.4	90	2.0	36

Table 2: Selected Water Quality Parameters and Nygaard Log Alpha Values for the Newfoundland LRTAP Lakes

LAKE	Distance from the	Nygaard Log Alpha	pH	Alkalinity mg/l	Water Colour	Depth M	Specific Conductance
1 Upper Indian	12.5	-0.280	6.0	1.8	50	3.5	14
2 Migaam	18.0	-1.400	6.7	17.7	15	17.0	54
3 Sandy	80.0	-0.520	6.1	10.5	55	2.0	25
4 Stephensons	30.0	-0.330	5.8	0.9	30	4.0	13
5 Wolf	50.0	0.317	5.2	0.5	100	1.0	15
6 Dolland	20.0	-0.420	5.9	1.5	30	3.0	15
7 Hungry Grove	30.0	-0.170	6.0	1.6	25	4.5	21
8 Glover Island	25.0	-1.020	6.3	5.5	60	4.0	21
9 Mosses Cove	0.5	-0.180	6.0	1.2	25	3.0	35
10 Gros Morne	5.0	-0.460	5.3	0.2	50	19.0	18
11 Jay	0.5	-0.150	6.0	3.2	70	1.0	31
12 Bog	5.0	-0.570	5.8	1.1	40	1.0	12
13 Long Waters	6.0	0.370	5.9	2.4	50	1.0	15
14 Chateaus	2.0	-0.220	5.9	2.0	100	1.0	20
15 Ochre Hill	3.5	-0.230	5.5	1.8	90	4.0	20
16 Rattle	0.7	-0.090	6.1	2.9	40	1.0	23
17 Nameless	2.5	-0.021	6.1	2.7	55	2.0	30

Table 3 : Multiple Linear Regression Analysis of pH , Log Alpha and Water Colour for the Kejimkujik and Newfoundland LRTAP Monitoring Lakes

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Kejimkujik

pH = -.378 * Log Alpha - 0.005 * Water Colour + 4.97
T= -5.3 *** -2.9**
RSQUARE= 0.86 N= 15 F= 39. **

Newfoundland

pH = -.408 * Log Alpha - 0.0046 * Water Colour + 6.1
T= -2.9 ** -2.0 *
RSQUARED= 0.61 N=16 F= 10.2 **

* P (.05 ** P (.01 *** P (.001

Table 4: Multiple Linear Regression Analysis Between pH and Selected Diatom Taxa for the Kejimkujik and Newfoundland LRTAP Lakes

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Kejimkujik

pH= -.024*Md -.099*M -.042*T +.032*F -.063*P -.019*N -.102*A + 5.3
T= -2.6** -8.9*** -4.0*** 3.7*** -3.3*** -2.2* -3.5**
RSQUARED= 0.93 N=15 F=14.***

Newfoundland

pH= -.025*MD -.023*M -.015*T -.037*S -.032*E +.064*P + 6.5
T= -2.8** -2.1* -2.6** -5.2*** -4.9*** 4.1**
RSQUARE= 0.86 N=17 F= 10.6***

* P < .05 ** P < .01 *** P < .001

Where

Md=Melosira distans
M=Melosira(excluding M.distans)
T=Tabellaria
F=Fragilaria
P=Pinnularia
N=Nedium
A=Actinella
S=Synedra
E=Eunotia

Table 5: Equations for Surficial Sediment Diatom Log Alpha vs Observed Lake pH from Published Figures (Adapted from Dickman et. al. , 1984)

Equation	Reference	Number of Lakes	Location
pH=6.62 - 0.65 * Log Alpha	Davis & Berge, 1980	29	Norway
pH=6.71 - 0.81 * Log Alpha	Merilainen, 1967	12	Finland
pH=6.97 - 0.46 * Log Alpha	Nygaard, 1956	13	Denmark
pH=6.63 - 0.81 * Log Alpha	Del Prete & Schofield, 1981	7	Central New England
pH=6.34 - 0.75 * Log Alpha	Norton et. al., 1981	31	Northern New England
pH=6.57 - 0.82 * Log Alpha	Dickman et. al.,1984	28	Lake Superior
pH=6.28 - 0.58 * Log Alpha	Davis & Anderson, 1985	31	New England
pH=6.56 - 0.64 * Log Alpha	Davis & Anderson, 1985	36	Norway
pH=4.49 - 0.77 * Log Alpha	This Study	15	Nova Scotia
pH=5.64 - 0.77 * Log Alpha	This Study	8	Newfoundland

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FIGURE 1. Map indicating Locations of the Lakes from which Surficial Sediment Diatom Samples were Collected.

FIGURE 2. Linear Relationship between pH and Log Alpha Values for the Nova Scotia Lakes.

FIGURE 3. Linear Relationship between pH and Log Alpha Values for the Newfoundland Lakes.

FIGURE 4. Downcore pH Reconstructions for Kejimkujik Lake using Regression Equations derived from both clear and coloured lakes.

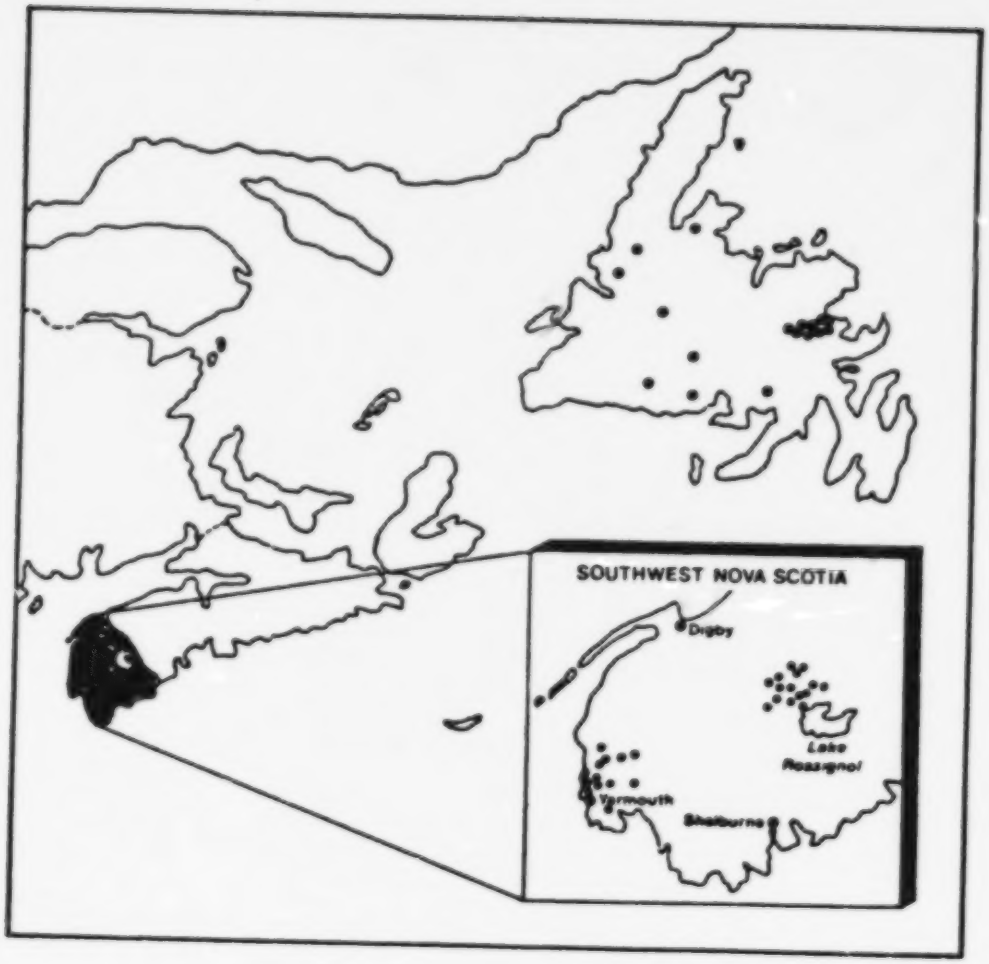
SOUTHWEST NOVA SCOTIA
Digby
Lake
Rossignol
Yarmouth
Shelburne

FIGURE 1

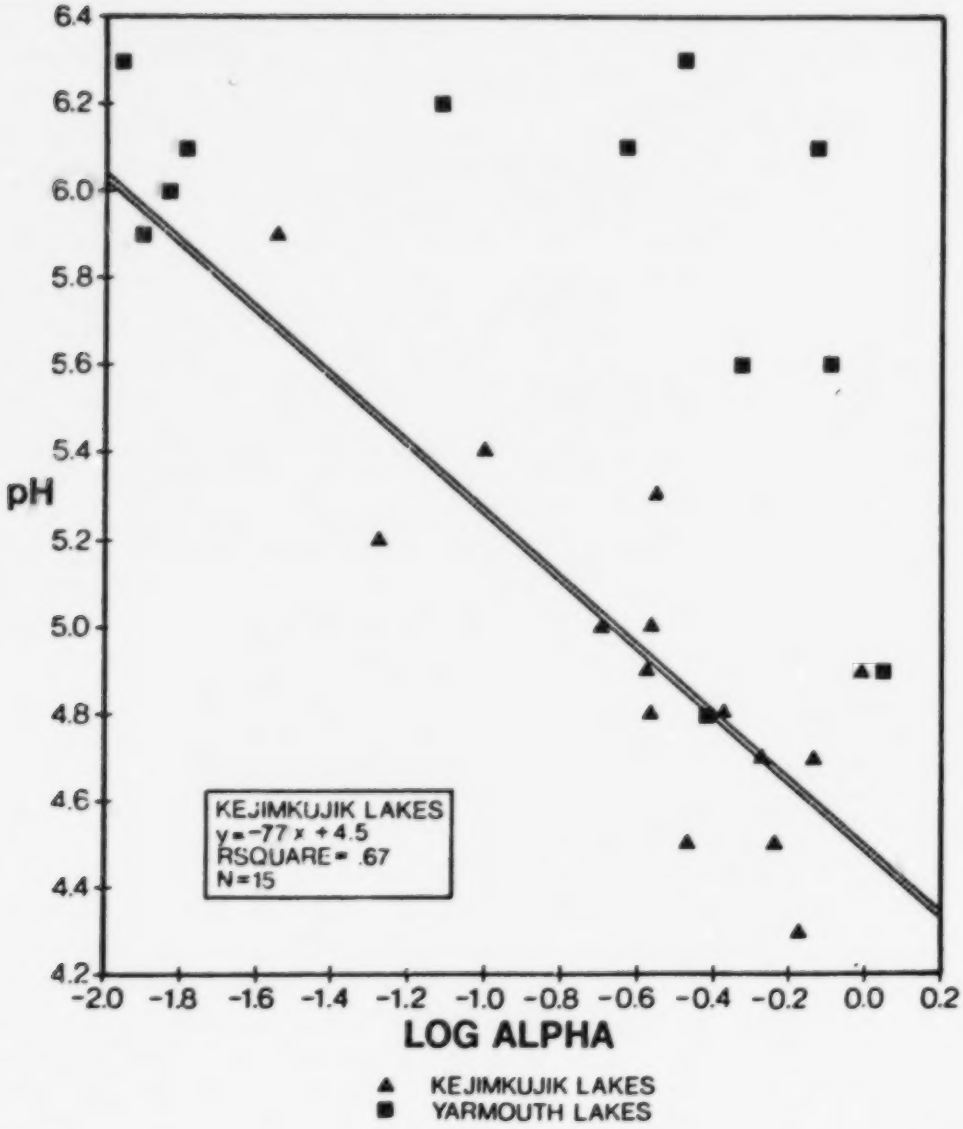
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
pH
KEJIMKUJIK LAKES
y=-77 x +4.5
RSQUARE= .67
N=15
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2
LOG ALPHA
KEJIMKUJIK LAKES
YARMOUTH LAKES

FIGURE 2

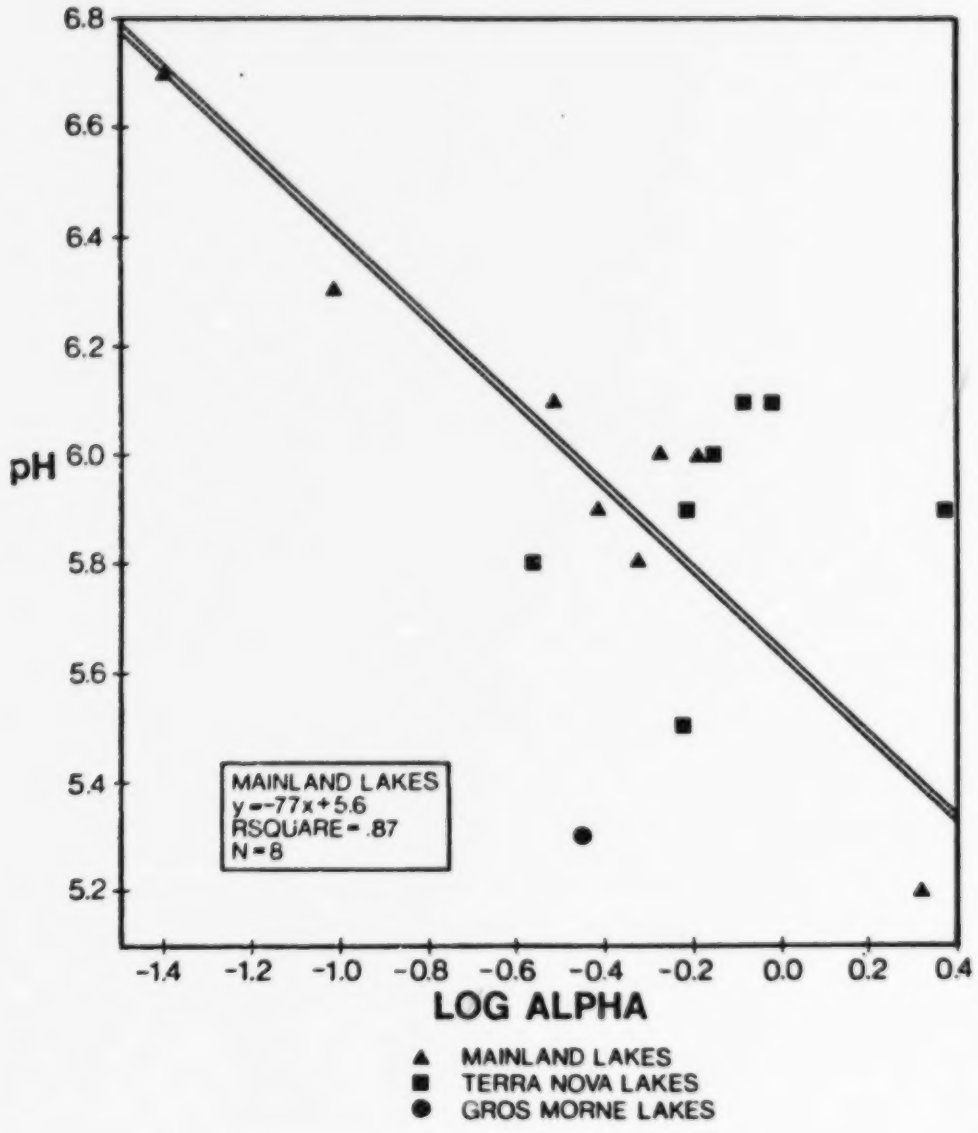
6.8
6.6
6.4
6.2
pH 6.0
5.8
5.6
5.4
5.2
MAINLAND LAKES
y = -77x + 5.6
RSQUARE = .87
N = 8
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
LOG ALPHA
MAINLAND LAKES
TERRA NOVA LAKES
GROS MORNE LAKES

FIGURE 3

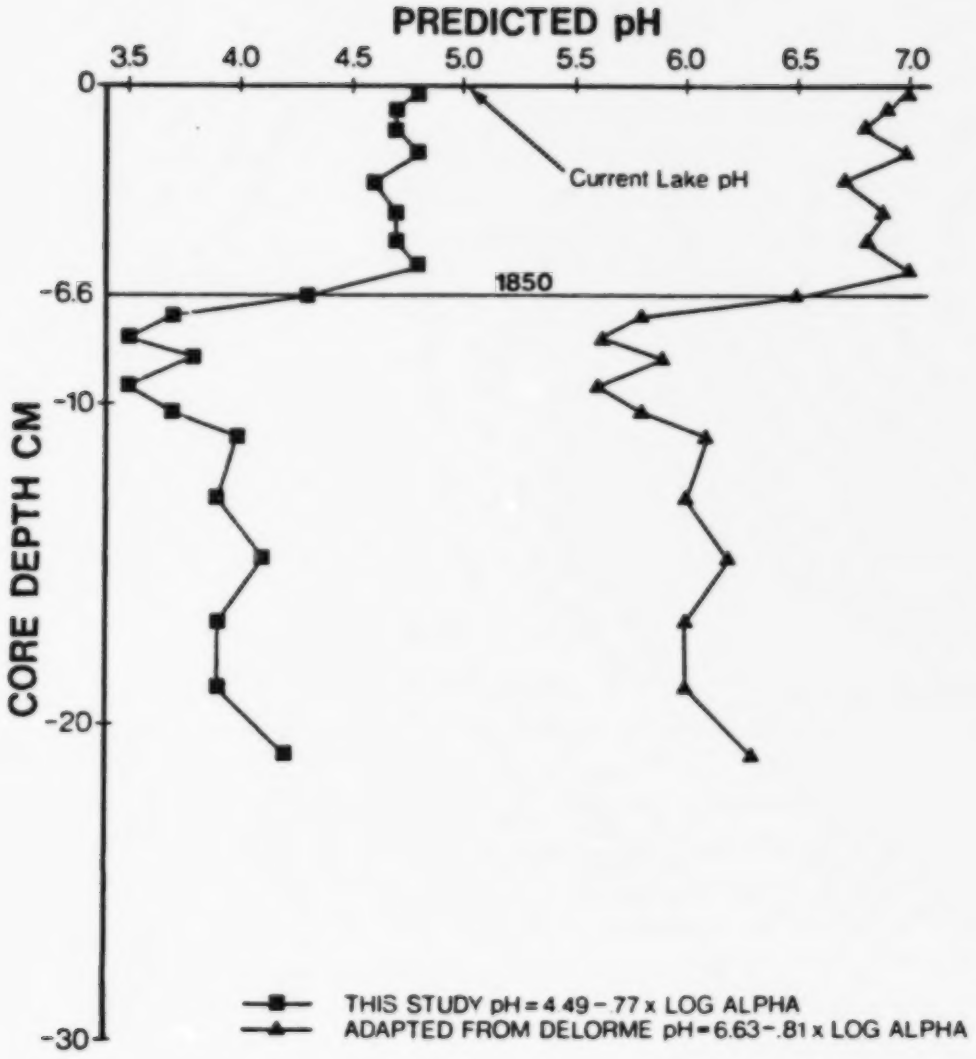
PREDICTED pH
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
0
-6.6
-10
-20
-30
CORE DEPTH CM
Current Lake pH
1850
THIS STUDY pH = 4.49 - .77 x LOG ALPHA
ADAPTED FROM DELORME pH = 6.63 - .81 x LOG ALPHA

FIGURE 4